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Investigation of LO-leakage cancellation and DC-offset influence on flicker-noise in X-band mixers

Rasmus Michaelsen[1,2], Tom Johansen[1], Kjeld Tamborg[2]
[1]Technical University of Denmark, Department of Electrical Engineering
2800 Kongens Lyngby, Denmark
Email: rsmi@elektro.dtu.dk
[2]Weibel Scientific A/S
3450 Allerød, Denmark

***Abstract*—This paper describes an investigation on the influences in 1/f noise of LO-leakage and DC-offset cancellation for X-band mixers. Conditions for LO-leakage cancellation and zero DC-offset is derived. Measurements on a double balanced diode mixer shows an improvement in noise figure from 14.3dB to 12.1dB at 10KHz, while maintaining a noise figure of 6.2dB at 1MHz. LO-RF isolation is improved from 18dB to 60dB. The 1/f noise is shown to increase with increasing DC-offset.**

***Index Terms*—Receivers, Mixers, 1/f noise**

I. Introduction

Direct-conversion receivers are used in Doppler radars, for defense and space applications [1] or for measuring human vital signs [2]. Another common application is to use direct-conversion to avoid complex image rejection structures [3]. Direct-conversion systems comes with drawbacks. One significant drawback is leakage, since the LO-signal and RF-signal is at the same frequency and isolation between those is in many applications an important criteria. Another problem is that the intermediate frequency is now at baseband and 1/f noise can be a great issue. There have been many proposals to reduce mixer 1/f noise in active mixers, common for many is that the steps used to reduce 1/f noise is to reduce the DC-bias current through the switching transistors. This either through a static principle [4] or using dynamic current injection [5], [6]. Also in passive transistor mixers a DC-offset results in an increased 1/f noise [7], [8]. In passive mixers where no bias is applied there still will be a DC-offset due to self mixing of the LO-signal that leak to the RF port.

In [9] a LO-leakage and DC-offset cancellation techniques is presented for direct conversion systems, and tested at 2.4GHz. In this paper the idea of this technique is expanded and used at X-band and tested using a 10.5GHz system. There will be derived conditions for when LO-leakage cancellation is obtained and when zero DC-offset is obtained. With this knowledge improved direct-conversion designs can be a possibility.

II. LO cancellation and DC offset

In a direct conversion system the LO and RF signal is at roughly the same frequencies. As the isolation between the LO an RF port of the mixer must be finite, there will be some leakage from one to the other. In passive mixers the LO drive level is typically quite high (many operates with a LO power of 7dBm or above [10]), this leads to a significant component of the LO signal at the RF-port. Instead of mixing the RF with the LO signal, actually it will be a sum of the RF and a leakage signal that is mixed with the LO signal. This self-mixing of the LO signal will give higher harmonic components and a DC off-set.

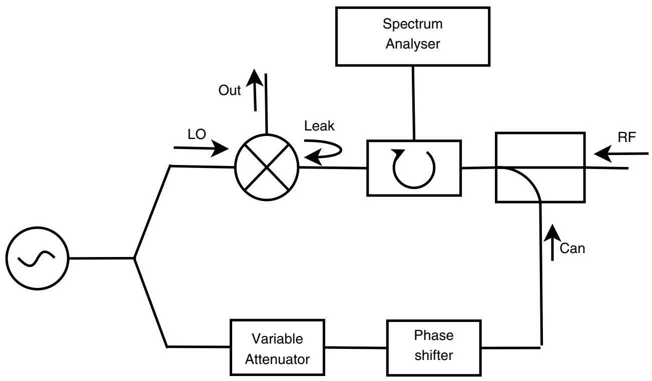

Fig. 1. Block diagram of the LO-leakage cancellation setup.

It is proposed in [9], to use a cancellation signal to remove the leakage signal. Figure 1 shows a block diagram of the method and defines the signals. The output signal, due to leakage and cancellation signals, at the IF port will then be given by (1)

$$\begin{aligned}S_{\text{out}}=&A_{\text{LO}}\cos(\omega t)\cdot\left[A_{\text{Leak}}\cos(\omega t+\phi_{\text{Leak}})\right.\\&\left.+A_{\text{Can}}\cos(\omega t+\phi_{\text{Can}})\right] \qquad (1)\\=&\frac{A_{\text{LO}}A_{\text{Leak}}}{2}\left(\cos(\phi_{\text{Leak}})+\cos(2\omega t+\phi_{\text{Leak}})\right)\\&+\frac{A_{\text{LO}}A_{\text{Can}}}{2}\left(\cos(\phi_{\text{Can}})+\cos(2\omega t+\phi_{\text{Can}})\right) \qquad (2)\end{aligned}$$

From (2) it is seen that the output is a signal with a DC part and a part with the frequency of the second harmonic. The second harmonic parts of (2) is easily removed by low pass

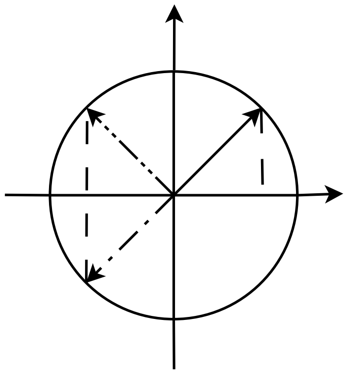

Fig. 2. Phasor of Leakage signal (solid arrow) and two possibilities of cancellation signals (dashed arrows). Only the single dotted cancels the leakage, whereas both cancel the DC-offset.

filtering, and the output is then given as (3)

$$S_{\text{out, lowpass}} = \frac{A_{\text{LO}}}{2}\Big(A_{\text{Leak}}\cos\left(\phi_{\text{Leak}}\right) + A_{\text{Can}}\cos\left(\phi_{\text{Can}}\right)\Big) \quad (3)$$

The criteria for cancellation of the leakage signal at the RF port is found from the part of (1) with the brackets. When this sum to zero, the cancellation signal will remove the leakage signal.

$$A_{\text{Leak}}\cos\left(\omega t + \phi_{\text{Leak}}\right) + A_{\text{Can}}\cos\left(\omega t + \phi_{\text{Can}}\right) = 0 \Leftrightarrow \quad (4)$$

$$A_{\text{Leak}} = A_{\text{Can}} \quad (5)$$

and

$$\phi_{\text{Leak}} - \phi_{\text{Can}} = \pm\pi \quad (6)$$

The criteria for a DC offset of zero can be found by setting (3) equal to zero.

$$\frac{A_{\text{LO}}}{2}\left(A_{\text{Leak}}\cos\left(\phi_{\text{Leak}}\right) + A_{\text{Can}}\cos\left(\phi_{\text{Can}}\right)\right) = 0 \Leftrightarrow \quad (7)$$

$$-\frac{A_{\text{Leak}}}{A_{\text{Can}}} = \frac{\cos\left(\phi_{\text{Can}}\right)}{\cos\left(\phi_{\text{Leak}}\right)} \quad (8)$$

Observe that to cancel the leakage the cancellation signal must have the exact same amplitude as the leakage signal and be out of phase, whereas to cancel the DC offset there is no such strict limit. Even when the amplitudes are equal there are two choices for the phase of the cancellation signal, such that the DC offset will be zero. Figure 2 illustrates this with phasors.

III. Measurements

A. Measurement setup

To test the cancellation technique two double balanced mixers each utilizing a MACOM MA4E2532L ring diode is used. One denoted 'Mixer 1' and the other 'Mixer 2', the difference between the two is in the matching circuitry. The X-band LO source is a custom made 10.52GHz oscillator. To measure the noise, a spectrum analyzer is used with a calibrated noise-diode, this setup uses the Y-factor method to measure the noise figure for the mixer [10].

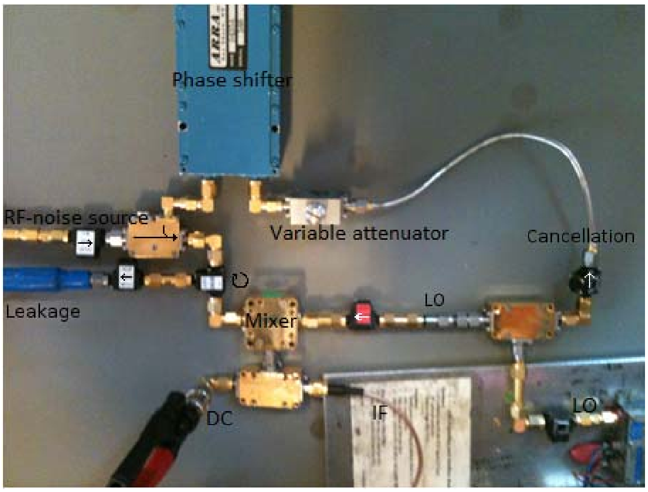

Fig. 3. Measurement setup

In figure 3 the cancellation setup is shown. The LO-signal is split in two parts using a matched T-split, one part is used to drive the mixer (the actual LO signal), the other part is used to generate the cancellation signal. To control the phase and amplitude of the cancellation signal a variable attenuator and phase shifter is used. The cancellation signal is coupled to the RF/Noise signal from the noise source, using a directional coupler with coupling of -15dB.

The DC offset is measured using a voltmeter, which is disconnected during noise measurements, to ensure that instrument noise is not influencing the measurement. A circulator is placed at the RF port of the mixer, this allows to measure the LO-leakage during measurements. After the circulator an isolator is used to ensure that reflections or noise from the instrument is not coupled to the setup. Isolators is used between all critical components to remove reflections and limit unwanted coupling in the system.

When starting a measurement the attenuator and phase shifter is tuned such that the measured leakage is as low as possible. This is done to set the cancellation amplitude equal to the leakage amplitude, which is the case when they cancel, as was predicted in (5). When the amplitude is set, the phase is swept to see the change in DC-offset, leakage, and noise figure.

B. Results

The mixer is measured to have an LO-RF isolation of 18dB and a noise figure of 14.3dB and 6.2dB at frequencies 10KHz and 1MHz respectively. Using the LO-cancellation technique the LO-RF isolation could be improved to 60dB. Figure 4 shows the LO-RF isolation and the DC-offset as a function of phase change in the cancellation signal. As was predicted in section II only one phase gives a leakage minima while there is two phases which gives a DC-offset of zero. The leakage minima and DC-offset is not located at the same phase, which according to (5), (6) and (8) is the case when the amplitudes are equal. After the full sweep there

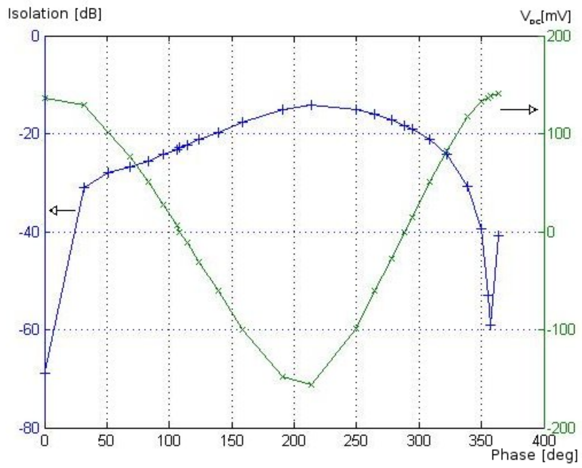

Fig. 4. LO-RF Isolation and DC-offset vs phase change.

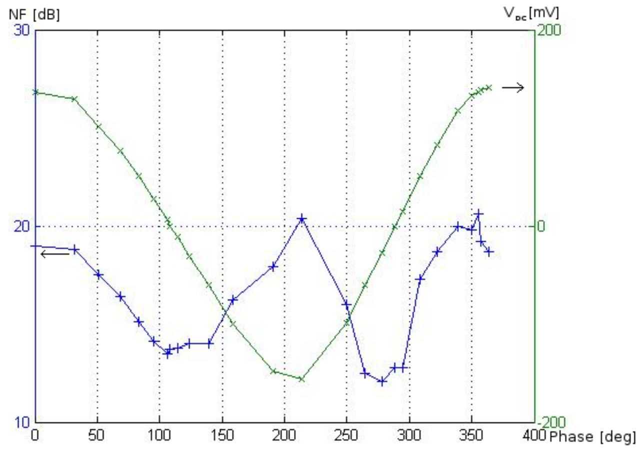

Fig. 5. Noise figure (10KHz) and DC-offset vs phase change, 'Mixer 1'.

was measured an amplitude difference of 1.5dB between the cancellation signal and the leakage signal, this is the reason for the difference in phase of the DC-offset zero and leakage minima.

If one wants the minimum LO leakage while achieving a DC-offset of zero, special care should be taken to match the cancellation signal amplitude to the leakage amplitude.

Using this technique can reduce the noise figure from 14.3dB to 12.1dB at 10KHz. In figures 5 and 6 the noise figure and DC-offset is plotted as a function of phase change in the cancellation signal. It can be observed that the noise figure is proportional to the magnitude of the DC offset, having minima when the DC offset is zero. Using the cancellation signal with a wrong phase will severely damage the mixers noise figure.

While the noise figure can be improved with 2dB at 10KHz there is no significant improvement at 1MHz. Rather at one of the zeros the noise figure is worse. In figures 7 and 8 the noise figure is plotted as a function of phase change in the cancellation signal for IF frequencies of 10KHz, 20KHz, 100KHz and 1MHz. It can be seen that for the low frequencies the improvement is largest, thus there must be a correspondence between the DC-offset and the 1/f noise. Comparing figure 5 and 7 it is clearly that the DC-offset increases the 1/f noise, thus one should try to avoid the DC-offset to get a better mixers regarding 1/f noise. Comparing figure 4 and 7 there is observed no correspondence between the noise figure and the leakage, thus it is concluded that the leakage has no influence on the 1/f noise except to generate the DC-offset.

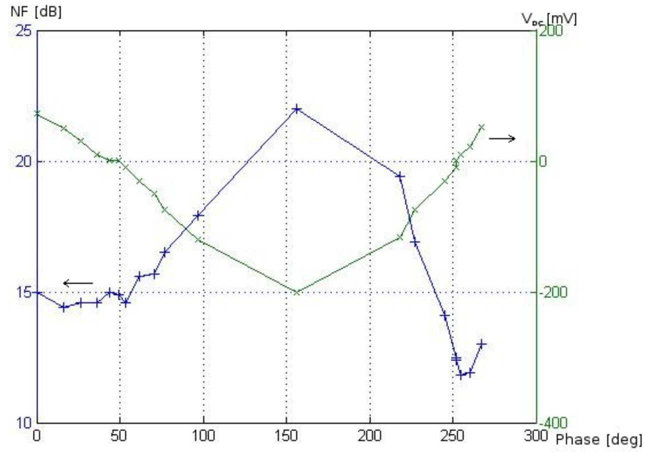

Fig. 6. Noise figure (10KHz) and DC-offset vs phase change, 'Mixer 2'.

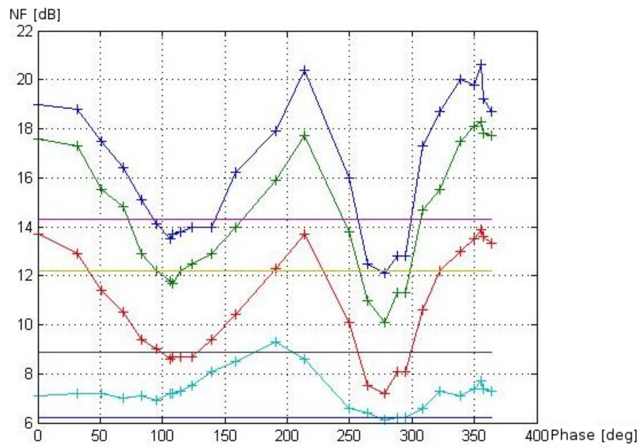

Fig. 7. Noise figure at different frequencies vs phase change, 'Mixer 1'. From top to bottom: Blue @10KHz, Green @20KHz, Red @100KHz, Cyan @1MHz (Straight line is without cancellation signal applied).

IV. Conclusion

A investigation on how LO-leakage and DC-offset effects 1/f-noise was conducted, using a LO-leakage cancellation method. For this method conditions for LO-leakage cancellation was derived together with conditions for zero DC-offset. It was shown that for leakage cancellation only one amplitude and phase will give full cancellation, whereas for zero DC-offset there is no strict limit to what the amplitude should be

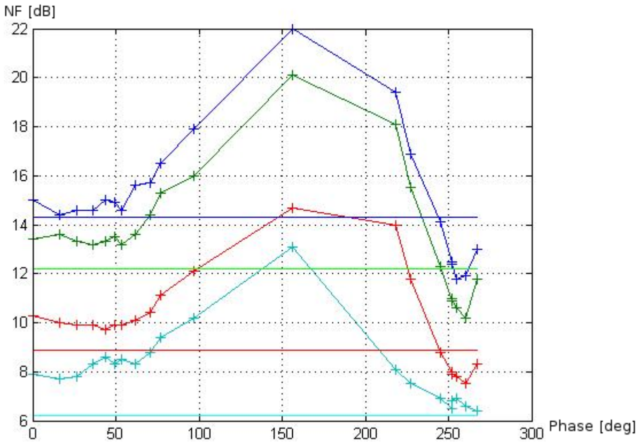

Fig. 8. Noise figure at different frequencies vs phase change, 'Mixer 2'. From top to bottom: Blue @10KHz, Green @20KHz, Red @100KHz, Cyan @1MHz (Straight line is without cancellation signal applied.)

and there can be up to two phases for a given amplitude which gives the desired result.

The cancellation method was tested using a double balanced ring diode mixer. LO-RF isolation was improved from 18dB to 60dB. Noise figure could be improved from 14.3dB to 12.1dB at 10KHz, while maintaining a noise figure of 6.2dB at 1MHz. It was shown that the 1/f noise increases as the absolute DC-offset is increased. While the LO-leakage does not effect the 1/f noise.

LO-RF isolation and zero DC-offset was in the measurement not obtained using the same cancellation signal. This was due to a amplitude mismatch between the cancellation signal and the leakage signal. In future designs utilizing this method one should take special care to match the amplitudes.

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